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Surface Roughness Influence on Eddy Current Electrical Conductivity Measurements

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ABSTRACT

The measurement of eddy current conductivity, in view of its frequency dependent penetration depth, has been suggested as a possible means to allow the nondestructive testing (NDT) of subsurface residual stresses in shot peened specimens. This paper addresses the apparent reduction of the near surface electrical conductivity measured by the eddy current method in the presence of surface roughness. Experimental results are presented on shot peened pure (C11000) copper, in which the effect is particularly strong and readily measurable because of the low penetration depth caused by the very high electric conductivity of the material. Eight shot peened samples between almen intensities 2 and 16 were thermally treated and tested by X-ray diffraction measurements until the residual stress and cold work fully dissipated, leaving only the surface roughness. Eddy current electrical conductivity measurements were carried out on each fully relaxed shot peened copper specimen over a wide frequency range from 1 kHz to 10 MHz. Our results show that surface roughness, acting alone, causes a strong apparent reduction of up to 10 to 20% of the measured electrical conductivity in shot peened copper. These results can be used to estimate the much smaller effect of surface roughness on the testing of shot peened turbine engine materials, which typically have approximately 100 times lower conductivity than pure copper and therefore exhibit 10 times higher penetration depth at the same test frequency. A comparison of the predicted underestimation of the electrical conductivity in the presence of surface roughness to the expected less than 1% conductivity increase due to compressive near surface residual stresses indicates that the described artifact can significantly affect eddy current testing of shot peened turbine engine alloys, such as Ti-6Al-4V or IN100.

Keywords: *eddy current testing, shot peening, residual stress, surface roughness.*

INTRODUCTION

Shot Peening

After final machining, tensile residual stress fields and microscopic surface discontinuities may be present in components, which could lead to crack initiation and propagation under cyclical loading if left untreated. Shot peening is a commonly used conditioning process which cold works the surface of metal components, resulting in a uniform roughness and a compressive residual stress layer that helps resist the potential for fatigue cracking. The shot peening process involves impinging the surface with a stream of uniformly sized spherical projectiles (that is, shot) at a given intensity (shot velocity) and percent dimple coverage. The plastic deformation generated by shot impacts causes an instantaneous tensile stress in the dimple and a subsequent contraction, resulting in a remnant compressive residual stress zone beneath the dimple. By overlapping the dimple coverage, a more or less uniform compressive residual stress is created over a shallow surface layer. Shot peening is performed on a wide range of materials, including gas turbine engine components, where the resulting combination of hardening and compressive residual stress improves resistance to fatigue, wear and corrosion (American Society for Metals, 1982).

Previous Work

It is generally accepted that, by using optimal shot peening conditions, fatigue life is increased, at least insofar as high cycle fatigue is concerned, and some researchers have proposed that this life credit may be transferred to engine components for life extension if, among other things, the near surface residual stress depth characteristics could be nondestructively measured with sufficient accuracy (John et al., 2001; Larsen et al., 2001). Unfortunately, there is not an established nondestructive testing (NDT) method, to the best of our knowledge, that can satisfy this engine component life extension proposition. However, development of potential methods for NDT of subsurface residual stress distributions is in progress. These potential nondestructive approaches include ultrasonic surface wave velocity dispersion (Thompson et al., 1996; Lavrentyev et al., 2000; Glorieux and Gao, 2000), eddy current electrical conductivity (Lavrentyev et al., 2000; Schoenig et al., 1995; Chang et al., 1999), alternating current potential difference (Matelect Systems, 1999) and thermoelectric (Carreon et al., 2002) methods. On the other hand, a number of established destructive methods are readily available to measure the depth profile of the resulting residual stress and these methods are essential to gauge the validity of nondestructive results. Among these, X-ray diffraction is probably the best suited for measuring the shot peening induced residual stress profile (Prevéy, 1990), which is based on the measurement of elastic strain from the lattice spacing (American Society for Metals, 1986).

From the standpoint of this paper, the most relevant research is that of Schoenig et al. (1995) and Chang et al. (1999), from which the authors concluded that eddy current electrical conductivity measurements offer a viable approach for residual stress assessment. However, this claim was not sufficiently substantiated by experimental evidence and subsequent studies came to the opposite conclusion. For example, Lavrentyev et al. (2000) found that the electrical conductivity of 7075 aluminum was not sufficiently sensitive to stress to allow nondestructive residual stress assessment in shot peened specimens, but may be useful for cold work measurements. The authors also found that the measured conductivity loss at higher frequencies and increasing peening intensities could be, to a large degree, caused by the induced surface roughness, although they did not investigate this effect in depth. It is apparent from these findings that some contradiction exists in the literature as to whether or not electrical conductivity may be used as a means of

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acquiring meaningful information on shot peening induced residual stresses. It is important to note that the former researchers were forming their conclusion from a component manufacturing perspective, while the latter researchers made their findings from the component service and maintenance perspective. One of the goals of this paper, in addition to documenting our results on surface roughness effects, is to shed some light on this apparent contradiction concerning the viability of eddy current electrical measurements for residual stress characterization.

From the turbine engine component maintenance point of view, NDT based residual stress measurements are thought to be complicated, not only by competing factors of surface roughness, plastic work and microstructure, but also by the relaxation of stress and cold working brought about by combined loading inside the extreme environment of the engine. Modern turbine engine alloys are designed to perform in this severe environment, but the precise effects of thermal, high cycle and low cycle fatigue loading on relaxation behavior are not well understood and could change from one alloy to another (Khadhraoui et al., 1997; Prevéy et al., 1998). Moreover, an in depth study of this problem would require considerable effort in light of the microstructural complexity of these mature engine alloys, the range of required testing and the high cost of destructive stress measurements.

Eddy Current Techniques

Eddy current NDT techniques have been practiced for several decades, primarily as a means of near surface discontinuity detection in metallic parts. For turbine engine applications, eddy current testing is the primary method used to test components for life limiting surface discontinuities and a great variety of probes have been manufactured to allow comprehensive testing of these complex components. The optimal frequency range of a given probe, and therefore its sensitivity and effective penetration depth, can be adjusted by manipulating the probe's diameter, the number of wire turns in the coil and the impedance matching circuitry. Eddy current probes are based on the electromagnetic induction principle, that is, that a changing magnetic field will induce electrical currents in a nearby conductor, which in turn will load the coil and affect the phase and magnitude of its impedance. Accurate measurement of these eddy current loading effects on the probe's impedance is the basis of most eddy current measurements and provides the means to test materials for near surface cracking and inclusions, heat treatment verification and, in some cases, thickness gaging. Of specific interest to this paper are those applications involving the eddy current measurement of electrical conductivity, where chemical composition, hardness, texture or stress state can significantly affect the property.

Eddy current conductivity measurements can be readily used for nondestructive characterization of shot peened surfaces. As an example, Figure 1 shows the measured relative difference in electric conductivity between the shot peened surface and the equivalent intact (unpeened) base alloy for a series of samples at six different

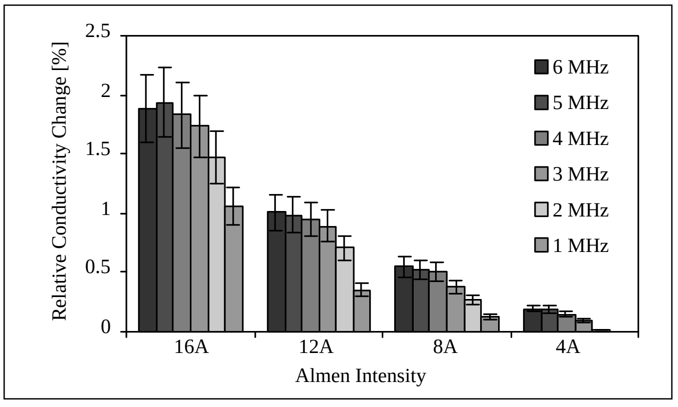

Figure 1 — The measured relative difference in electrical conductivity between the peened surface and unpeened equivalent surfaces for a series of samples at six different frequencies.

frequencies (samples consist of an age hardenable, nickel based commercial alloy). The measurements were made on a computer controlled scanning system, using an eddy current unit with a built in leveling platform to maintain a common liftoff as the scanning takes place. Conductivity blocks of 1.03% and 1.48% on the International Annealed Copper Standard (IACS) scale were used to calibrate the sensitivity of the eddy current probe from 1 MHz to 6 MHz in accordance with the standard practice (*ASTM E 1004-99*). These measurements clearly demonstrate that electrical conductivity is significantly affected by shot peening, especially at higher almen intensities. Unfortunately, the net change in eddy current conductivity is a superposition of all of the three major effects of shot peening, so it is not clear what aspect of shot peening is of primary importance and how the conductivity change may be weighed in reference to the peening induced residual stress, cold work and surface roughness, which are all known to be significantly affected by the peening intensity. It is also apparent from the higher almen intensities of Figure 1 that the test frequency has a measurable influence on conductivity. In general, the greatest difference in the measured conductivity occurs at the highest frequency, that is, when the penetration depth of the eddy current is the lowest. However, this expected behavior is not always apparent in other materials, where the electrical conductivity measured on the shot peened surface is either higher or lower than that of the intact material and the observed frequency dependence is less pronounced. The complicated dependence of the measured eddy current conductivity on peening intensity in different materials indicates that, for shot peening, a combination of competing factors determines the observed trends. However, the effect of shot peening on electrical conductivity is always quite modest, at around 1 to 2%. In order to better understand the relative role of the three principal effects of shot peening in this complex phenomenon, one should separately investigate them, a daunting task by any standard. The easiest thing to do is to eliminate the two material effects of shot peening (stress and cold work) by appropriate heat treatment, leaving only the surface roughness unchanged from the initial condition.

PREPARATION OF COPPER SPECIMENS

The separation of variables described above can be most easily achieved in pure copper, which is used as a universal reference material in eddy current measurements. We selected pure (99.9%) cold rolled copper C11000 as a model material for the following experiments because of its microstructural simplicity and its ease of dissolution of shot peening induced residual stress and cold work. Another advantage of using pure copper is that the stress and cold work may be fully relaxed by annealing at modest temperatures with only minimal changes to the microstructure, leaving surface roughness as the sole evidence of shot peening. It is also very important that the phenomenon investigated in this work, namely the adverse effect of surface roughness on eddy current electrical conductivity measurements, is much easier to study in copper than in other materials of lower conductivity. The strength of this effect is determined by the ratio of certain surface parameters, such as the root mean square roughness and the correlation length, to the relevant yardstick of eddy current conductivity measurements, namely the standard penetration depth. In turbine engine materials, which typically have approximately 100 times lower electrical conductivity than pure copper and therefore exhibit 10 times higher penetration depth at the same test frequency, the effect is relatively small and more difficult to investigate quantitatively.

Microstructure

The microstructure of pure copper comprises a single phase. Cold rolling during manufacturing usually results in the presence of trapped bulk residual stresses and a modest but measurable texture, which we have attempted to minimize by stress annealing the bars as a first step at 873 K (1110 °F) for 30 min in a nitrogen flooded chamber to minimize oxidation. Figure 2 shows the measured Rockwell F hardness of cold rolled C11000 copper (filled circles) as a function of annealing temperature in a vacuum furnace for 30 min. There is a sharp drop at around 713 K (824 °F), where recrystallization occurs.

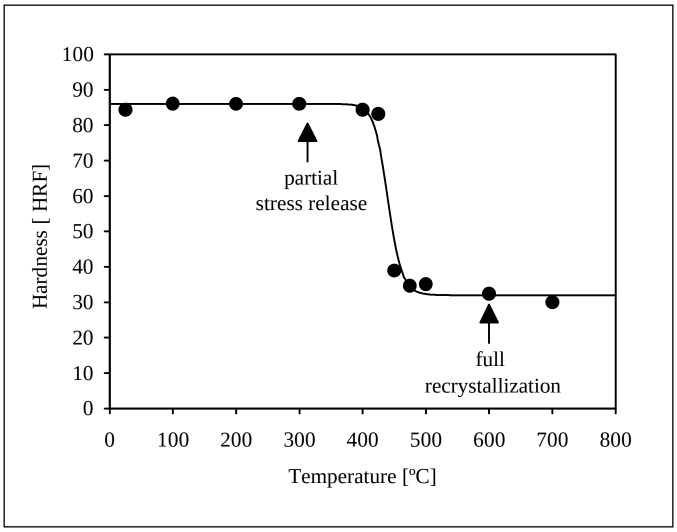

Figure 2 — Rockwell F hardness measurements showing a sharp drop corresponding to the C11000 copper recrystallization temperature at about 713 K (824 ˚F), which served as a baseline for the thermal relaxation of shot peened samples.

However, cold working is known to dramatically lower the annealing temperature in C11000 copper (American Society for Metals, 1996), so it was expected that the relaxation of residual stress and cold work would occur below the base metal recrystallization temperature due to the presence of a higher degree of cold work directly below the shot peened surface. After the initial stress annealing, the bars were shot peened at various intensities, using commercially available Z600 glass beads of 0.6 to 0.9 mm (0.02 to 0.03 in.) in diameter to a nominal coverage of 100%. Each copper sample was 500 mm (19.7 in.) long by 38.1 mm (1.5 in.) wide by 12.7 mm (0.5 in.) thick and shot peening was done over a 25 by 25 mm (1 by 1 in.) area on the 38.1 mm (1.5 in.) face of the bars at three well separated locations per bar.

Annealing

Our ensuing relaxation study on shot peened electrolytic copper showed that, unlike surface roughness, which is essentially independent of thermal loading, both the residual stress and cold work effects can be effectively eliminated by appropriate annealing. In order to monitor the gradual decay of residual stresses and cold work after successive steps of annealing at increasing temperatures, comprehensive X-ray diffraction measurements were conducted by Lambda Research of Cincinnati. We have found that in pure copper the cold work effects disappear well before full stress relaxation occurs (Carreon et al., 2002). As an example, Figure 3 shows the residual stress and cold work distributions in shot peened copper specimens

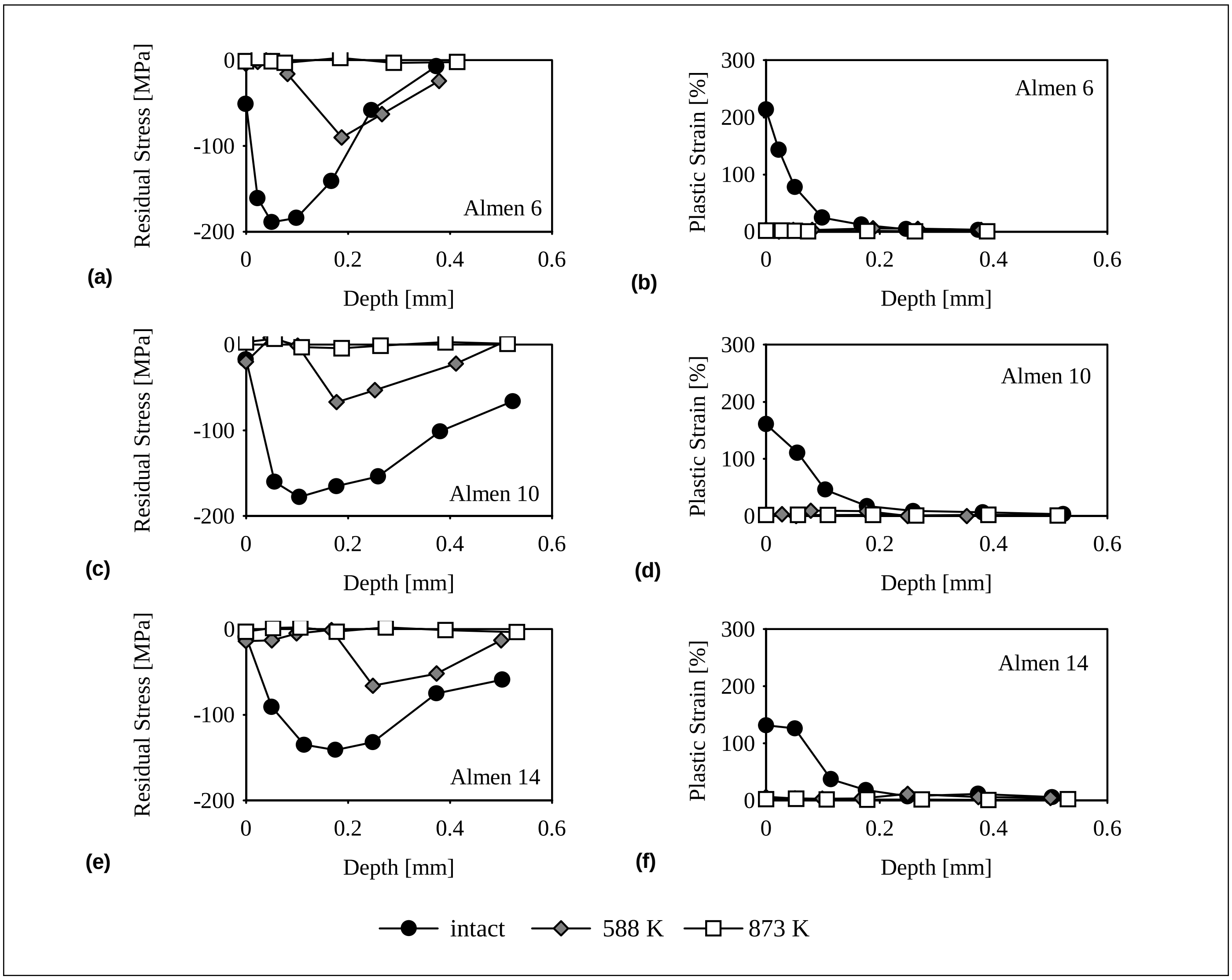

Figure 3 — Subsurface residual stress and cold work distributions in intact, partially stress released and completely annealed copper specimens as measured by X-ray diffraction: (a) stress distribution in almen 6 sample; (b) cold work distribution in almen 6 sample; (c) stress distribution in almen 10 sample; (d) cold work distribution in almen 10 sample; (e) stress distribution in almen 14 sample; (f) cold work distribution in almen 14 sample.

in three stages of relaxation for three different peening intensities. The first series was tested directly after shot peening (solid circles), the second series (gray diamonds) was partially stress released for 30 min at 588 K (599 ˚F), while the third series (empty squares) was fully annealed for 30 min at 873 K (1110 ˚F). The residual stress data taken from the intact shot peened specimens without stress release show that the maximum compressive layer can always be found slightly below the surface. Generally, the results indicate increasing depth of compression with increasing intensity. The surface residual stress slightly decreases in magnitude as the peening intensity increases, which is typical of work hardening materials. The residual stress data taken after a 588 K (599 ˚F) partial stress release show a substantial reduction in residual stress at all almen intensities while the 873 K (1110 ˚F) annealing, well above the recrystallization temperature, completely eliminated the remaining residual stress.

The same X-ray diffraction data can also be used to quantitatively assess the degree of cold work below the shot peened surface by testing the diffraction peak width, which significantly increases as a result of cold working. The results taken before partial stress release indicate that maximum cold work occurs at the surface of the shot peened samples. The maximum cold work does not differ significantly with peening intensity, however the depth of the plastically deformed layer appears to slightly increase with increased peening intensity. In contrast to the more persistent residual stress, the cold work is essentially gone after the 588 K (599 ˚F) partial stress release at all three almen intensities. Another effect of cold work on the material is the development of a localized subsurface texture, which can also be studied by X-ray diffraction. Figure 4 shows the plane (200) back reflection pole figures for the highest peening intensity (almen 16) C11000 copper specimen before and after annealing for 30 min at 588 K (599 ˚F): light and dark gray indicate areas of 50 to 100% and 100 to 200% intensity relative to the average, respectively. The lack of preferred orientation in the azimuthal direction indicates that the initial annealing successfully removed the original texture of the bar stock as intended. After shot peening, the plane of the surface still remains essentially isotropic, but the emergence of a perceivable polar texture clearly shows the effect of substantial plastic deformation at the surface. It was found that, like the subsurface cold work, this texture was also completely eliminated by annealing at 588 K (599 ˚F) for 30 min as indicated by the “spotty” appearance of the pole figure after annealing. In polycrystalline materials, texture can be either morphologic or crystallographic in origin. Although shot peening can lead to both kinds of texture, it should be mentioned that the crystallographic type, which is actually measured by X-ray diffraction, is not expected to cause a detectable variation in electrical conductivity in cubic materials like copper since cubic crystals are completely isotropic (Blodgett and Nagy, 1998). Still, the disappearance of the crystallographic texture indicates that morphologic texture caused by various features, such as oriented dislocations, slip bands and grain boundary imperfections, have also vanished. In conclusion, the fully annealed copper specimens are free of all primary material effects of shot peening and are suitable for studying the only remaining secondary effect by itself, that is, the influence of surface roughness on eddy current conductivity measurements.

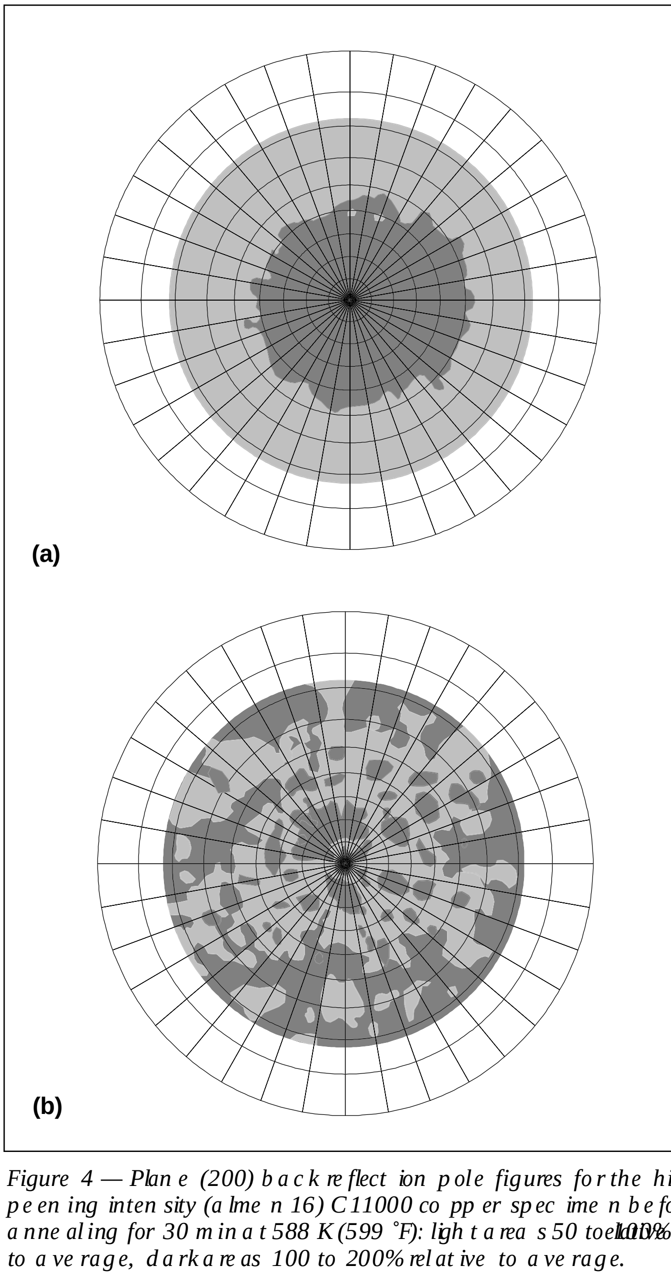

Figure 4 — Plane (200) back reflection pole figures for the highest peening intensity (almen 16) C11000 copper specimen before and after annealing for 30 min at 588 K (599 ˚F): light areas 50 to 100% relative to average, dark areas 100 to 200% relative to average.

SURFACE CHARACTERIZATION

The impact of shot on a deformable metal surface will leave characteristic dents or dimples at each point of impingement. With tight control of the shot peening parameters, components may be treated such that the entire surface is uniformly covered with partially overlapping microscopic shot dimples. In some cases, a component may be shot peened to 200% coverage or more to increase the hardness. However, for turbine engine components, the main goal of shot peening is to achieve 100% coverage to maximize the beneficial residual stress effect with minimal plastic work. The surface roughness resulting from shot peening is essentially random but exhibits fairly uniform statistical behavior, which is commonly characterized by two statistical parameters, namely the root mean square roughness R_q and the correlation length Λ. The surface height distribution is usually close to a normal (gaussian) distribution with a standard deviation equal to R_q. The correlation length is derived from the autocovariance function, which is calculated by multiplying the surface profile with itself after laterally shifting it by varying amounts and averaging the product over the entire inspected surface. The type of autocovariance function, that is, the way the average product decreases with increasing lateral shift, depends on the type of surface treatment used to roughen the specimen. In the case of shot peening, the autocovariance function can be usually best fit with an exponential decay with the correlation length Λ being defined as the $1/e$ drop from the zero lag position on the autocovariance function, which provides a measure of the nominal in plane periodicity of the surface roughness (Bennett and Mattsson, 1989).

Measurement Acquisition

Our surface roughness measurements were collected using a scanning optical profilometer. The instrument is specifically equipped to perform surface metrology over a broad range of scales from profiling microscopic scratches on optical lenses to thickness gaging on various mechanical and electronic devices. This instrument has two primary modes of operation: phase shifting interferometry, which is mainly used for measuring microscopic surface features under high magnification with 0.3 nm (1.2×10^{-8} in.) vertical resolution; and vertical scanning interferometry, which is used in

cases involving vertical displacements up to 500 μm (0.02 in.) while resolving vertical features as small as 3 nm (1.2×10^{-7} in.). The lateral resolution is approximately 0.5 μm (2×10^{-5} in.) for phase shifting interferometry and approximately 12.5 μm (5×10^{-4} in.) for vertical scanning interferometry, depending on the magnification. For our case, we used the vertical scanning interferometry mode of operation with an effective magnification of 2.6, which allowed surface features to be mapped at high resolution over a 1.8 by 2.3 mm (0.07 by 0.09 in.) sampling area. For vertical scanning interferometry, the degree of fringe modulation or coherence is the basis of the roughness measurement. White light is used as the probe source and the interference fringe modulation is measured and analyzed in real time to provide spatially averaged results over the sampling region (Caber, 1993; Bhushan et al., 1985). The fringe modulation originates from the optical path difference between the reference and image arms of the instrument during vertical scanning (Lee and Strand, 1990).

With the chosen instrument settings, the vertical and lateral performance of the scanning optical profilometer was more than sufficient to accommodate the mild surface roughness imparted via shot peening to the copper samples. In order to examine the roughness uniformity, 16 individual measurements were collected, consisting of root mean square roughness and both X and Y axis autocovariance plots, for each shot peening intensity. The average root mean square roughness for the different peening intensities is shown in Figure 5, where the error bars represent ±3 standard deviations (±3σ) of the mean roughness to provide a conservative error estimate. Similarly, the correlation lengths were based on the average of the 32 individual best fit autocovariance functions (two directions at each measurement location). Figure 6 shows the average correlation length for the nine different peening intensities with error bars representing ±30% of the average for a conservative estimate of the error.

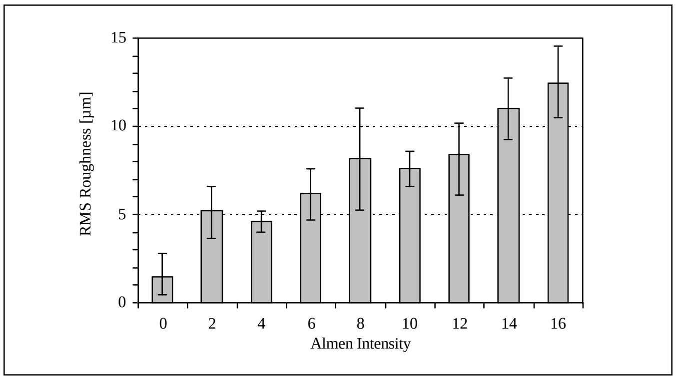

Figure 5 — The average root mean square (RMS) surface roughness values based on 16 individual measurements for each different shot peening intensity in pure copper.

Clearly, the root mean square roughness of the shot peened copper samples tends to increase with increasing peening intensity. Almen intensity is determined by the degree of curvature imparted to a standard almen strip (SAE1070 spring steel), which ensures repeatability of the shot peening process. Almen "A" strip thickness is 1.29 mm (0.05 in.). The curvature is due to residual stresses resulting from shot impingement on only one side of the strip. The degree of curvature is a means of gaging the energy of the shot stream. The observed roughness trend is consistent with the idea that higher shot energy results in deeper dimple impacts. However, it is notable that the samples peened at almen 2A and 8A were nominally rougher than their higher intensity neighbors. This irregularity may be due to the fact that, in terms of shot peening quality control, the uniformity of the surface roughness is not a primary consideration; rather, the shot intensity and coverage are the main control variables. A likely reason why surface roughness is not a key consideration is that shot peening is typically done on alloys significantly harder than pure copper. Therefore, the resulting roughness is virtually imperceptible at low peening intensities and only very modest at higher intensities.

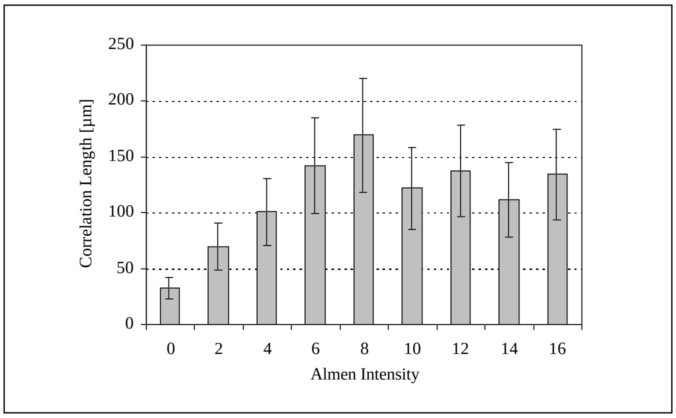

Figure 6 — The average correlation lengths for each different shot peening intensity based on a collection of 16 by 2 best fit autocovariance plots.

EDDY CURRENT MEASUREMENTS IN ROUGH COPPER SPECIMENS

The electrical conductivity measurements on our fully relaxed shot peened copper samples were performed by an eddy current instrument using a series of probes to assure optimal sensitivity over a wide frequency range from 1 kHz to 10 MHz. At each test frequency, the instrument and the probe were calibrated by a four point linear interpolation procedure using two calibrated reference blocks of σ_1 = 100.3 % and σ_2 = 78.5 % (on the IACS scale) and an s = 0.08 mm (3.2×10^{-2} in.) thick polymer foil for controlling liftoff (above 4 MHz the thickness of the polymer foil was reduced to 0.03 mm [1.2×10^{-3} in.]). Figure 7 shows a schematic representation of the coil impedance in the complex plane before (Figure 7a) and after (Figure 7b) zoom in. For a given set of gains and phase rotation, the "real" (or horizontal) $X = X(\sigma, l)$ and ìimaginary" (or vertical) $Y = Y(\sigma, l)$ components of the measured impedance are determined by the conductivity of the specimen σ and the liftoff distance l.

First, the four reference points are measured on the two calibration blocks with ($l = s$) and without ($l = 0$) the polymer foil between the probe coil and the specimens. Then, the coil impedance measured on the rough specimens was tested in terms of apparent conductivity and liftoff using simple linear interpolation (though the liftoff data were subsequently discarded). It should be mentioned that the linear interpolation technique, which is known to leave much to be desired over larger measurement ranges, was quite sufficient over the relatively small conductivity range considered in this study. Because of the high precision requirements of these measurements, efficient rejection of inevitable liftoff variations is of the utmost importance. It was also necessary to periodically repeat the calibration procedure in order to reduce the adverse effects of thermal drift caused by the weak, but still perceivable instability of the probe and the instrument. The statistical variations over the 25 by 25 mm (1 by 1 in.) shot peened areas were kept under control by repeating all measurements at 50 different locations and averaging the data, which also reduced the incoherent scatter in the data caused by thermal oscillations, electrical noise, imperfect liftoff rejection and so on. With such measures, the accuracy of the averaged data is expected to be better than 0.5% IACS, which is quite sufficient for the limited purposes of this study, that is, for the demonstration of the overall magnitude and qualitative frequency dependence of the apparent conductivity loss caused by surface roughness. It should be mentioned, however, that a quantitative comparison of the experimental data to analytical models to be developed in the future will also require extensive ensemble averaging, that is, averaging over different representations of a given statistical class of surface roughness. In the present study, each almen intensity was represented by a single specimen, therefore the quantitative conclusions one might draw from the measured data are inherently limited by statistical considerations rather than by the accuracy of the measurements.

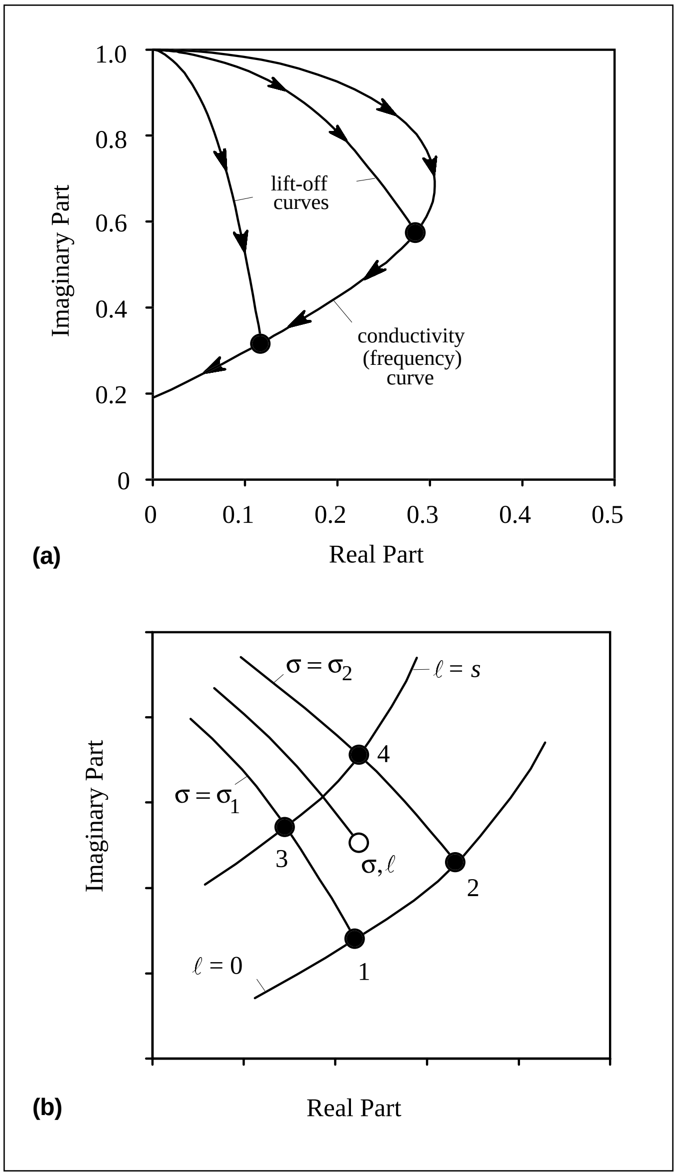

Figure 7 — A schematic representation of the coil impedance in the complex plane: (a) before zoom in; (b) after zoom in.

Results

Figure 8 shows the measured apparent electrical conductivity of nine C11000 specimens of varying surface roughness as a function of frequency. The apparent conductivity loss significantly increases with peening intensity, which in turn is related to the surface roughness of the specimens; in each case the measured conductivity decreases with frequency. The frequency dependent apparent electrical conductivity is expressed in terms of percent IACS. The symbols represent the average of fifty measurements on the different rough specimens, while the solid lines are best fitting trend lines of the common form

(1) $$\sigma = \sigma_0 \left[\frac{1 + \left(\frac{f}{f_2} \right)^n}{1 + \left(\frac{f}{f_1} \right)^n} \right]^{\frac{1}{n}}$$

where

f = the test frequency and σ_0, f_1, f_2 and n are adjustable parameters.

Physically, σ_0 is the intrinsic volumetric conductivity of C11000 copper, while the other three parameters are related to the surface roughness. For all specimens, σ_0 = 101.3% IACS, f_1 = 1 MHz and n = 0.8 were kept constant, while f_2 was varied to fit the data. The ratio of the two characteristic frequencies, $\eta = f_2 / f_1$, is a measure of the overall (apparent conductivity) loss and will be called the "loss factor." The dependence of this loss factor on the peening intensity is shown in Figure 9. Clearly, a strong correlation exists between the peening intensity and the apparent conductivity loss as measured by η. It should be mentioned that the empirical form of the best fitting function of Equation 1 was arbitrarily chosen and is not expected to provide any insight into the underlying physical phenomenon. In spite of its very low surface roughness, the unpeened reference specimen (almen 0) also exhibited a measurable loss of conductivity at high frequencies. It is possible that at these levels, other surface phenomena besides surface roughness can contribute to the observed loss at high frequencies. Therefore it might be prudent to subtract this baseline from all the other data measured over the surface treated areas, thereby isolating the sought roughness effect of shot peening. However, this baseline effect is very small and we decided to present the raw data without any correction.

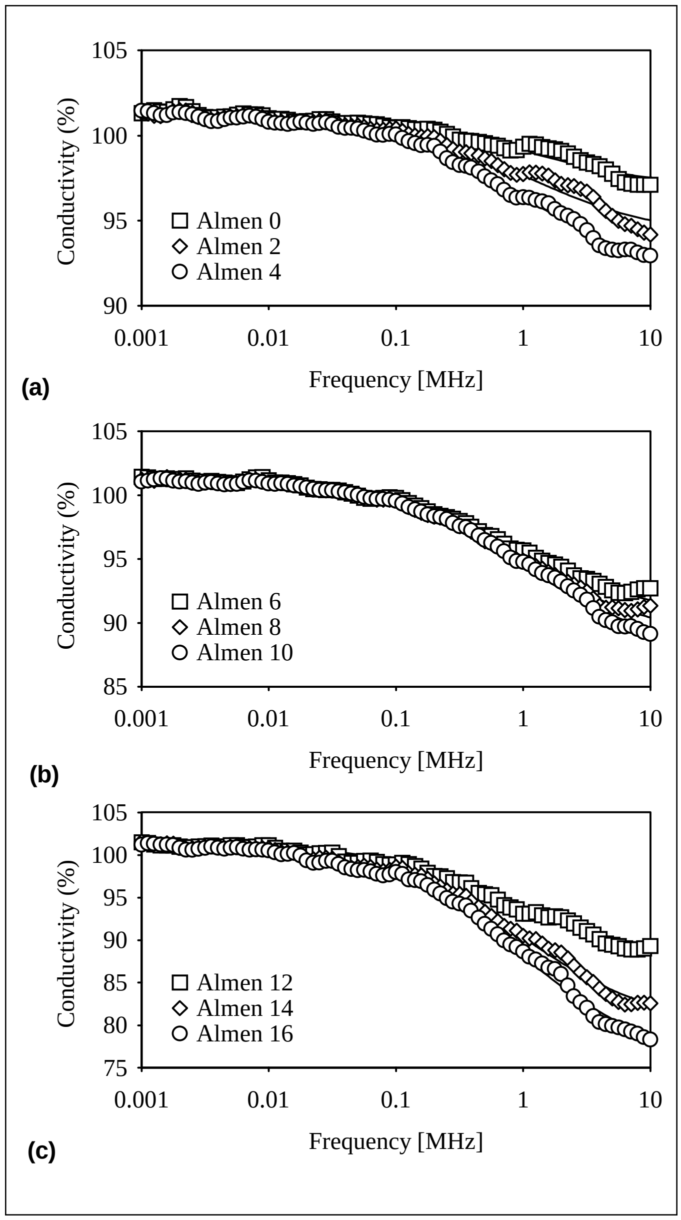

Figure 8 — The measured apparent electrical conductivity of nine C11000 specimens of varying surface roughness as a function of frequency.

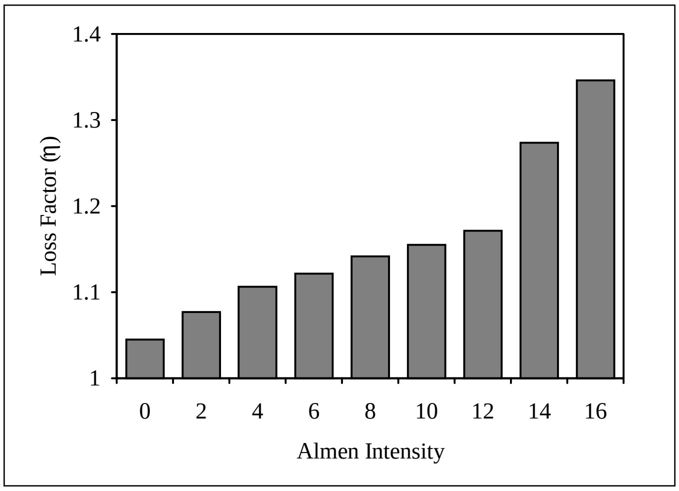

Figure 9 — The loss factor η defined in Equation 1 as a function of the peening intensity.

Interestingly, the correlation of the apparent loss of conductivity with peening intensity is as good or even better than with the surface roughness. This is somewhat unexpected since, as we mentioned above, the root mean square surface roughness does not correlate particularly well with the peening intensity. For example, specimen A8 exhibited slightly larger root mean square roughness (8.2 μm [3.2×10^{-4} in.]) than A10 (7.6 μm [3×10^{-4} in.]) but produced weaker conductivity loss. Although currently there are no analytical models available to predict the dependence of the apparent conductivity loss on the root mean square roughness and the correlation length, it is clear that a more tortuous path results in a larger degree of apparent conductivity loss. Therefore, beside the absolute value of the root mean square roughness, the characteristic ratio of the correlation length to the root mean square roughness also plays a very important role. As it turns out, specimen A8 features the largest correlation length of all specimens, which reduces the effect of its rather high root mean square roughness and most probably is responsible for its relatively modest conductivity loss.

These results show that surface roughness, acting alone, can cause an apparent reduction of up to 10 to 30% of the measured electrical conductivity in annealed copper. The apparent conductivity loss caused by surface roughness is determined by the ratio of the root mean square roughness to the standard penetration depth of the eddy current and is also affected by the tortuosity of the surface that can be characterized by the root mean square roughness to correlation length ratio. Based on our experimental results, one can estimate the much smaller effect of surface roughness on the testing of shot peened turbine engine materials of lower conductivity. For example, for a given surface roughness, the apparent loss of electrical conductivity in Ti-6Al-4V (1% IACS) at 5 MHz is expected to be the same as in annealed pure copper (100% IACS) at 50 kHz, that is, as much as 1 to 2% for peening intensities ranging from 6 to 12 almen. Even after accounting for the fact that typical peening intensities tend to result in approximately 2 to 3 times as high roughness in copper (5 to 10 μm [2×10^{-4} to 3.9×10^{-4} in.] root mean square) than in much harder engine materials (2 to 4 μm [7.9×10^{-5} to 1.6×10^{-4} in.] root mean square), one has to conclude that the expected underestimation of the electrical conductivity in the presence of surface roughness will be comparable to the expected less than 1% conductivity change due to compressive near surface residual stresses, which indicates that the described artifact will significantly affect eddy current testing of shot peened turbine engine alloys. It should also be mentioned that the ratio between the sought conductivity change due to the presence of residual stresses and the spurious apparent conductivity loss caused by surface roughness significantly decreases during thermomechanical relaxation. Therefore, the described artifact plays an even more important role in the eddy current testing of engine components after long term service than directly after surface treatment.

CONCLUSIONS

The apparent loss of electrical conductivity caused by the inherent surface roughness of shot peened specimens was studied by experimental means. Our measurements were carried out on shot peened pure copper, in which the effect is particularly strong and readily measurable because of the low penetration depth caused by the very high electric conductivity of the material. The shot peened samples were thermally treated and tested by X-ray diffraction measurements until the residual stress and cold work fully dissipated, leaving only the surface roughness. We have found that depending on the surface roughness and the test frequency, the apparent conductivity loss can be as high as 10 to 30%. In high strength, high temperature engine materials like titanium alloys and nickel based superalloys, the electrical conductivity is only around 1 to 2% IACS and consequently the eddy current penetration depth is fairly high, approximately 2 to 300 μm (7.9×10^{-5} to 1.2×10^{-2} in.) at 5 MHz. In comparison, the root mean square roughness of typical shot peened surfaces is on the order of 2 to 4 μm (7.9×10^{-5} to 1.6×10^{-4} in.). In the absence of quantitative models to predict the influence of such weak surface roughness on the measured electrical conductivity, one might be inclined to assume that the effect is negligible. However, our experimental evidence strongly suggests that this is not true and that, if left uncorrected, the spurious geometrical effect of surface roughness could significantly distort, and even overshadow, the sought residual stress effect. This is because the total change of electrical conductivity caused by the presence of elastic strains in most nonmagnetic materials is merely 1 to 2% at close to the yield point of the material and even less if residual stresses were to be detected after thermomechanical stress relaxation.

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